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Fusion Research: The Past is Prologue

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ABSTRACT

At this juncture fusion research can be viewed as being at a turning point, a time to review its past and to imagine its future. Today, almost 50 years since the first serious attempts to address the daunting problem of achieving controlled fusion, we have both an opportunity and a challenge. Some predictions place fusion research today at a point midway between its first inception and its eventual maturation - in the middle of the 21st century - when fusion would become a major source of energy. Our opportunity therefore is to assess what we have learned from 50 years of hard work and use that knowledge as a starting point for new and better approaches to solving the fusion problem. Our challenge is to prove the "50 more years" prophesy wrong, by finding ways to shorten the time when fusion power becomes a reality. The thesis will be advanced that in the magnetic confinement approach to fusion open-ended magnetic confinement geometries offer much in responding to the challenge. A major advantage of open systems is that, owing to their theoretically and experimentally demonstrated ability to suppress plasma instabilities of both the MHD and the high-frequency wave-particle variety, the confinement becomes predictable from "classical," i.e., Fokker-Planck-type analysis. In a time of straitened budgetary circumstances for magnetic fusion research now being faced in the United States, the theoretical tractability of mirror-based systems is a substantial asset. In pursuing this avenue it is also necessary to keep an open mind as to the forms that mirror-based fusion power plants might take. For example, one can look to the high-energy physics community for a possible model: This community has shown the feasibility of constructing large and complex particle accelerators using superconducting magnets, vacuum chambers and complicated particle-handling technology, housed in underground tunnels that are 20 or more kilometers long. In the paper examples of mirror-based fusion power systems resembling long "linear colliders" will be discussed.

It is not the intent of this paper to present detailed proposals for next-generation experiments in magnetic fusion research, but rather to encourage a return to the ambiance of an earlier era of fusion research, when innovative thinking and a spirit of scientific adventure prevailed. In that way we can realistically build a new era of fusion research, an era that would be firmly undergirded by the scientific and technological foundation that was laid in fusion's first half-century.

I) Introduction

The title of this paper, "Fusion Research; The Past is Prologue," is intended to focus the reader's attention on two aspects of the fusion quest as it is viewed by the author today. The first of these aspects, one that is especially apparent to anyone who has been involved in this research from its early days, is the maturity of today's understanding of the complexities of plasma behavior as compared to those early days. Starting, in the 1950s, with a relatively primitive knowledge of the plasma state that arose mainly from the study of electrical discharges in gases, fusion and space-physics researchers built a whole new scientific discipline - the physics of high-temperature plasmas. In the fusion-related case of the magnetic confinement of plasmas there exists today theory and computational expertise undergirding a truly prodigious data base on the behavior of plasmas at fusion-relevant densities and temperatures. And yet, despite this knowledge base we find ourselves without the means to define a fully satisfactory practical implementation of this understanding in the form of a viable fusion power system.

Thus the second aspect of the title, "prologue," is intended to address the question of the future of magnetic confinement fusion, in particular the issue of innovation aimed at finding better, simpler, less expensive approaches to fusion power than the present ones that are based on the "closed" or toroidal approaches such as the tokamak or the stellarator. As such it will represent an appeal to "cast a wider net" in our search for better approaches. Out of the author's biases and predilections, it will also represent an appeal to the fusion community to explore the potentialities of open-ended systems in this search.

Looking back over the history of magnetic fusion research it is not difficult to discern how closed systems, such as the tokamak, came to dominate the research scene. Their relative simplicity, their appealing empirical scaling laws (confinement time increasing as the square of the plasma radius) and their theoretical intractability (which forced an empirically based approach to progress) led to the construction of larger and larger facilities. The central theme of the tokamak campaign was, and still remains, "better confinement, hotter temperatures, and closer approach to the Lawson Criterion (i.e., $n\tau$, the product of plasma density and plasma confinement time, must exceed a critical value) for plasma ignition." In a time of uncertainty as to the viability of the basic concept of the magnetic confinement of hot plasmas, this theme was certainly a valid one. However, in seeking to achieve the ultimate goal of fusion research, namely, economic fusion power, that campaign theme is too simplistic.

While the world-wide emphasis on the tokamak approach has resulted in major achievements in plasma temperatures and confinement times, now approaching those needed for fusion power, it has at the same time led to a sobering circumstance: Based on the extrapolation of those same results, results that were so painstakingly achieved, the tokamak in its present form is seen by significant numbers of the fusion research community as being too large and cumbersome, and too fraught with serious practical problems, to ever become an economical source of fusion electrical power.

Thus a paradox: The positive aspect of the tokamak, i.e., that it has demonstrated the viability of the concept of the magnetic confinement of fusion-relevant plasmas, has been accompanied by a negative result: If the tokamak in fact does not represent a viable fusion power system, the decades-long preoccupation of the fusion community with research on closed systems has meant that research on the "orthogonal" alternative, that is, open-ended magnetic systems, has languished. Specifically it has languished to the point that today only one or two research groups in the world are seriously studying this alternative. With this diminution in effort there also comes an erosion of the understanding of the physics of such systems on the part of the fusion community. One purpose of this paper will therefore be to review some critical aspects of the concept of plasma confinement in open systems.

However, if it accomplishes no other objective, the main message that this paper is aimed at delivering is to encourage the fusion community, particularly its younger members, to take a serious look at the open-ended magnetic field topology, its characteristics and its inherent advantages (and its problems to be overcome) from a fusion standpoint. From this vantage point there may then be seen to exist new approaches to fusion power, ones that are simpler and less demanding than the closed-geometry genre, and ones that have a more promising future than those systems. The example system sketched in the concluding sections of this paper is included to illustrate a small subset of the many opportunities for innovation possessed by open-ended fusion systems. The type of system envisaged in this example may or may not represent a viable fusion approach in the long run.

II) Defining the Goals of Fusion Research

The pursuit of magnetic fusion research has had many different goals over the nearly 50 years that it has been conducted. In the earliest days "the first thermonuclear neutrons" was a chimerical goal that was only a diversion. This goal was replaced by a more reasonable, but still stultifying one: the pursuit of ever-higher density-confinement-time products ($n\tau$ values). A positive effect of pursuing this new goal (which originated from the previously mentioned "Lawson Criterion" for net fusion power) was to focus the research on plasma instabilities and on ways to ameliorate their destructive effect on confinement. In time a negative effect of this goal was to cause, worldwide, the near abandonment of approaches that did not obviously extrapolate to high confinement $n\tau$ values, e.g. open systems such as the mirror machine. Now, after the tokamak has come to dominate the research scene, the research goal has shifted toward the achievement of the “ignition” of a deuterium-tritium (D-T) plasma, even if it is to be achieved in systems whose long-range economic viability is questionable. The D-T plasma ignition concept is, in turn, narrowly defined as that circumstance when the kinetic energy deposited (and retained) in the plasma by the 4.5 MeV alpha particle fusion reaction product is sufficient to maintain the plasma in steady state at fusion temperatures in the face of the cooling effects of radiation losses, transport losses across the confining magnetic field, and the energy required to heat up injected cold D-T fuel. Pictured as the long-awaited victory in “lighting the fusion fire,” this goal is easily understood by everyone, but it, too, misses the real mark.

In charting a possible new course for fusion research the research goals chosen should not be ones that unnecessarily restrict the types of fusion systems that are to be investigated. They should also be goals that are seen to be compatible with the long range goal of fusion research itself. That broader goal, one that has been implicit in all that has been done to date, could be stated as follows: “To generate net power from fusion reactions at a competitive cost, and with superior environmental and safety characteristics as compared to other energy sources.” Within this goal, the goal of “net power” is clearly the first step of the task. If we then, as is the convention, define a fusion parameter “Q” as the ratio of the fusion power produced to that required to sustain the fusion reactions, this first step is to achieve the condition $Q > 1$. This goal is not the same as, and is much less restrictive than, the one presently adopted by tokamak community: Their goal, that is, the one of plasma ignition, corresponds to achieving the condition $Q = \infty$.

Systems with finite Q values, especially including ones with Q values not much larger than unity, are so-called “driven” systems. They are ones where a substantial portion of the generated fusion power is recirculated in order to heat the fuel to fusion temperatures. We have discussed the implications of operating at low Q values in open-ended fusion systems in previous publications [1,2]. Operation at low-Q values clearly places much more modest demands on plasma $n\tau$ confinement parameters than does the requirement for ignition, shifting the burden to the technological tasks of achieving efficient plasma heating and efficient energy recovery from both fusion reaction products and the unreacted fusion fuel ions. In this sense driven fusion power systems are analogous to a well-known thermal-mechanical system, the gas turbine. This highly successful net-power producer is one in which the amount of power internally recirculated (from the turbine to the compressor) is actually substantially larger than the net output power. In the development of the gas turbine achieving useful net power required the steps of maximizing the efficiencies of both the compressor and the turbine.

Freeing fusion research from the goal of achieving ignition and substituting the long-range goal of achieving net power allows the consideration of a much wider range of possible systems, while at the same time reducing the requirements on the most intractable part of magnetic fusion research, that of extending the confinement time up to the limit $Q = \infty$. Once this new goal is accepted the task of fusion research becomes more evenly divided between the plasma-science-related goal of extending plasma confinement times and the technological goals of developing efficient means for injecting and heating fuel ions and of efficiently converting particle kinetic energies into electricity. In the next section I will recapitulate some of the attributes of open-ended magnetic fusion systems that seem to me to make them prime candidates for an era of new beginnings in fusion research.

III) Open-Ended Field Topology: Distinctive Characteristics

Although perhaps not evident at first glance, the topological distinction between "closed" and "open" magnetic confinement systems is the source of profound differences in their attributes in confining plasmas. These differences are reflected in both the plasma-physics aspects of their confinement and in the practical aspects of their incorporation into fusion systems. To review the special characteristics of open systems that are relevant to the present discussion, they are:

1. Open-ended field configurations exist that permit MHD-stable confinement at high beta values. As shown by theory [3] and by experiment [4] in open-field geometry it is possible to form true "magnetic wells" within which plasmas whose plasma pressure approaches that of the confining field (i.e. $\beta = 1.0$) can be confined. Figure 1 illustrates the field configuration of a quadrupole magnetic well as produced by a "baseball" coil (a coil whose windings resemble the seam on a baseball). Such coils, first suggested at the Culham Laboratory in the United Kingdom, were employed in many mirror experiments.

2. In open-ended systems, where there exist two loss channels (transverse, across the field lines, and longitudinal, out the open ends) it is not necessary for the confined plasma to terminate, either in the radial direction or axially, on a nearby physical surface. In closed systems, having only a single loss channel, i.e. across the field lines, the plasma must terminate on a close-lying material surface, resulting in steep temperature and density gradients. These gradients can represent an important source of turbulence and cross-field losses for closed systems, one that need not occur in open systems. In an open system

the radial plasma boundary can be far inside the chamber wall and the end-leaking plasma can be made to terminate on a large surface located far from the confinement zone.

3. Taking advantage of the ambipolar nature of plasma end losses from open-ended systems it is possible to establish localized regions of elevated plasma potential, thus controlling or inhibiting the loss of particles out the ends, as in the tandem mirror [5,6]. Also, the fact that the end-exiting plasma can be caused to terminate on surfaces whose potential can be controlled externally means that it is possible to vary the plasma potential with radius in a pre-determined way, allowing the suppression of certain classes of drift instabilities, as has been demonstrated in the Gamma 10 tandem mirror experiment [7] at Tsukuba University in Japan.

4. The end-loss channel of open systems makes them especially adaptable to the use of high-efficiency direct converters [8.9] located at the ends and intercepting the flow of charged fusion reaction products and energetic fuel ions that escape before fusing. The use of direct converters is an essential element in achieving operation at low fusion Q values.

5. Open systems, particularly ones operating at low Q values, can contain plasmas that are characterized by ion distribution functions that are non-maxwellian, i.e., ones that are less randomized than those normally encountered in closed systems. This property is important when it is desirable to suppress satellite neutron-producing reactions (for example, in a D-He3 fueled system [10]), or to increase the efficiency of direct conversion systems, whose efficiency is higher the narrower the ion energy distribution.

In summary, it should be evident that removing the topological constraint that is imposed on closed systems, namely, that the flux surfaces of the confining field must close on themselves within the confinement chamber, has a profound effect on the "living space" of open-ended systems. This non-quantifiable characteristic of flexibility means that there is much more room for innovation and adaptation to particular requirements in open-ended systems than there is with closed systems.

In trying to understand why these listed advantageous characteristics of open-systems, ones that seem so apparent, have not been adequately recognized and exploited by the fusion research community, we return to the issue of goals alluded to earlier. From the onset of research in open-ended systems the issue of controlling end losses has been a stumbling block. As long as there existed uncertainty as to the viability of the whole idea of magnetic confinement those who made fusion policy were likely to come down on the side of systems for which the problem of end losses did not exist. This bias was not a serious problem as long as fusion budgets were healthy enough to allow breadth in the program, but when belts are tightened conservatism tends to have the upper hand. However, today we are presented with a new situation, one in which the conservative approach is seen to possibly lead to a dead end, and when new thinking is required. As illustrated by the distinctive characteristics that have been listed, I believe that open systems represent a fertile area for such new thinking.

IV) Open-Ended Field Topology: Plasma Physics Characteristics

As a result of now nearly fifty years of research on open-ended systems there exists a large body of information, including theory and corroborating experimental data, on such systems. In fact, throughout the history of research on open-ended systems there has always been a close affinity between the theory and experiment. By contrast, closed systems have often been found to be intractable to analysis, owing to the complexity of the plasma physics issues involved.

In this section I will briefly review the main theoretical developments in open systems and their corroboration by experiment.

A) Mirror Confinement and Adiabatic Invariants

This section briefly reviews the history of the particle-dynamic aspects of the confinement of plasmas in mirror systems. In this connection, one of the earliest-considered issues in the confinement of plasmas in mirror-based systems related to the constancy of the magnetic moment, μ, of the plasma particles as they gyrated back and forth between the mirrors. The magnetic moment is defined as the ratio of the particle's kinetic energy associated with the component of its velocity perpendicular to the field lines to the local value of the magnetic field:

$$\mu = \frac{W_\perp}{B} \quad \text{Joules/Tesla} \tag{1}$$

Early theoretical work, for example that by Kruskal [11] established the validity of the concept of the adiabatic invariant (asymptotic invariance of the quantities, such as the magnetic moment, under slow changes of parameters). Later work (described below) related this to the problem of mirror confinement of charged particles.

The repelling force on a gyrating particle that is exerted by the magnetic mirrors (regions of increased magnetic field) is given by the equation:

$$F_z = -\nabla(\mu B) = -\mu\nabla(B) \quad \text{Newtons} \tag{2}$$

The quantity (μB) thus acts as a "potential energy" for motion along the field lines. When, in an increasing magnetic field, this potential energy becomes equal to the parallel component of energy at the lowest point in the field, the particle will be stopped and reflected, analogous to the back-and-forth motion of a rolling ball trapped between two hills. An equivalent statement of this condition is that the pitch angle made by the particle as it traverses the midplane must be greater than the "loss cone" angle, θ_c , where

$$\mathrm{Sin}(\theta_c) = (1/R)^{1/2} \ , \tag{3}$$

where R is the "mirror ratio," B_m / B_0 , the ratio of the magnetic field at the peak of the mirror, B_m , to that at the midplane, B_0 .

The first question to be asked, the one addressed by Kruskal, is the following: Under what conditions is it valid to assume that the magnetic moment remains constant as the particle bounces back and forth between the mirrors? As was shown by Kruskal, and by others following him, the magnetic moment is an adiabatic invariant. That is, its fluctuations during the course of its motion between the mirrors becomes exponentially small with the reciprocal of an "adiabatic parameter," α, equal to the ratio of the magnetic gradient scale length, L_m , to the gyroradius, a, of the particle, i.e., $\alpha = a/L_m$. The relationship therefore takes the form

$$\frac{\delta\mu}{\mu} = A \exp(-B/\alpha), \tag{4}$$

with constants A and B being of order unity in typical cases. As can be seen, the fluctuations become vanishingly small in the limit of small α. At typical fusion-relevant magnetic field strengths, particle energies, and apparatus physical dimensions, the adiabatic parameter is indeed quite small and fluctuations in μ arising from this source are usually unimportant.

Although the adiabatic invariance of μ insures that, in the absence of other perturbing effects (such as particle-particle collisions), trapped particles will remain trapped between the mirrors as far as their axially directed motion is concerned, it does not answer a subtler question: In bouncing back and forth between the mirrors, will the particles perform a random walk across the flux surfaces of the field until they hit the wall? This problem was addressed, and elegantly solved by Northrop and Teller [12]. They recognized that, in addition to the adiabatic invariant μ there is also operative another adiabatic invariant, J, the "action" integral, defined as the integral of the parallel velocity component of the particle between the turning points of the longitudinal bouncing motion of the particle as it is reflected by the mirrors. Specifically,

$$J = \int_{-L}^{L} v_{par}\, ds \qquad m^2\ sec^{-1} \tag{5}$$

The existence of the J invariant insures that bouncing particles, though drifting azimuthally, will, in absence of other perturbing forces, remain on a closed surface (corresponding to a flux surface in the limit of small cyclotron radius of the particle). One therefore has a situation where in the limit of sufficiently weak extraneous perturbations (for example, collisions), particles trapped between the mirrors will remain trapped "forever." This situation is in marked contrast to that in closed systems, for example the stellarator, where there exist classes of initially trapped particles that are compelled to drift across the field to the container wall.

The power of the two invariants to maintain trapping was dramatically illustrated, in 1958, in the ARGUS experiment, proposed by N. Christofilos. In this experiment, one that will in all likelihood never be repeated, a rocket launched a payload consisting of a small nuclear weapon into the ionosphere. When detonated, the nuclear explosion released a cloud of energetic electrons (from beta decays). Electrons from this cloud were mirror-trapped in the earths's magnetic field, and drifted azimuthally to form an artificial Van Allen belt which could be detected by sounding rockets. Ten years later it was still possible to observe the presence of such electrons, after they had made some billions of reflections.

Similarly striking confirmations of the power of the invariants to insure long-time confinement of energetic electrons in mirror fields were made in 1959 in an experiment by Rodionov [13], and in 1962 in experiments by Gibson, et. al. [14]. In both experiments electrons from the beta decay of a radioactive gas were trapped in situ between mirrors and their confinement times were measured and compared to the predicted lifetime from collisions of the electrons with background gas atoms. Confinement times corresponding to millions of reflections, in close agreement with those predicted by scattering theory, were found.

While collective effects, such as those discussed later, can certainly vitiate confinement in mirror-based systems, it is also true, as has been demonstrated in the laboratory, that when these collective effects are suppressed by choice of the field geometry and plasma parameters, confinement times are found approaching those predicted from "classical" inter-particle collisional effects expected in a quiescent plasma. To my knowledge this situation has never been encountered in a closed confinement geometry. In closed systems of all types there seems always to exist, at some level, turbulence that results in cross-field transport substantially in excess of the "classical" predictions.

Having determined the good confinement characteristics of mirror-based systems in the absence of collisional processes, the next necessary step is to calculate the effect of inter-particle collisions in causing losses through the end mirrors. It was early on recognized that in a simple mirror machine the confinement time would be limited to times of order of a mean ion-ion collision time, at which time there would be a high probability of an ion to have been scattered into the loss cone. To perform a meaningful calculation of the loss rate the Fokker-Planck equation was employed, incorporated into computer codes. Early fundamental work in this area includes work by Rosenbluth, McDonald and Judd [15], who formulated the problem and deduced the nature of the solution. As a result of their work, and of later work by many others [16,17], the steady-state "classical" density-confinement-time product for mirror systems with a mirror ratio, R, was found to be relatively accurately expressed by a relationship of the form:

$$n\tau \;=\; k_i \; E_i^{3/2} \; \log_{10}(R) \quad \mathrm{m^{-3}\ sec.} \qquad (6)$$

Here E_i is the mean ion energy, and the constant k_i depends on the ion type and on the details of the means by which the ions are introduced into the system (i.e. whether as monoenergetic beams and at what angle of injection relative to the field lines. For deuterons and perpendicular injection k_i was found to be approximately 2.5×10^{16} . As an example of the implications of this result, one must plug in a mirror ratio as high as 10 and an ion energy of 100 keV to achieve an $n\tau$ value of 2.5×10^{19} , marginal as far as allowing the production of net fusion power ($Q > 1$) from the D-T reaction. This marginality hung over the Mirror Machine as a Sword of Damocles throughout its development. One result was to stimulate the invention of high-efficiency direct converters to increase the effective Q value of mirror-based systems. Another, and very significant, result was the invention of the Tandem Mirror concept by Dimov and Fowler and Logan. Still another was the introduction of the idea of multiple mirror systems (a linear array of linked mirror cells) by Post [18] and Budker [19].

Despite the marginality of the confinement time in simple mirror systems as predicted by the Fokker-Planck analyses, the confinement time predicted by this means stood as a well-defined "standard" against which to compare experimental results. To achieve confinement times approaching this standard required understanding and avoiding (or stabilizing) collective effects in the plasma, including both MHD modes and high-frequency instabilities. The fact that this feat was accomplished represents a major achievement of the mirror research community.

B) MHD Interchange Modes

From early on the issue of MHD stability has been addressed in open-ended systems of the mirror type. The first mirror machines employed simple axially symmetric fields. In such fields although the field-line curvature near the mirrors is convex toward the plasma, i.e., stabilizing for MHD interchange modes, the curvature near the midplane is concave toward the plasma (field weakens with radius). As shown in the original paper of Rosenbluth and Longmire [20], except for special ion distributions ("sloshing ions") that have density maxima near the mirrors, the line-averaged pressure-weighted curvature of such fields, is net negative, i.e., unstable. Since some early experiments, such as the "Table-Top" experiment at Livermore exhibited stable behavior when the theory indicated instability [21], other stabilizing mechanisms were postulated, which, under special circumstances could overcome the destabilizing effects of bad curvature. One such mechanism, predicted theoretically [22], is the so-called "line tying" effect, resulting from plasma electrical conductivity, along the field lines and through the mirrors to an external conducting surface, suppressing interchange modes by "shorting out" their electrically driven drifts. Still another stabilizing mechanism, effective against higher-order interchange modes, is that arising from the so-called "finite-orbit" effects, as predicted by Rosenbluth, Krall, and Rostoker [23]. They showed that the relative azimuthal drifts of ions and electrons (because of their different cyclotron radii), as they move up and down between the mirrors, can stabilize MHD interchange modes.

Although the above stabilizing mechanisms (line-tying and finite-orbit effects) may be operative in some experiments, they are not as potent as the field-configuration-related stabilizing effect, first demonstrated in the now-famous experiments by Ioffe [24]. In these experiments Ioffe showed that by introducing non-axially symmetric field components (created by axial conductors - the "Ioffe bars" - a "magnetic well" could be created within which the plasma was rendered robustly stable against all MHD-type modes. As later demonstrated theoretically by Taylor and Hastie [3], and subsequently verified in the 2XII experiment [4] of Coensgen et. al. at Livermore, the stabilizing effect of a magnetic well is so strong that plasmas with energy densities approaching that of the confining field ($\beta = 1$) can be stably contained. In a further extension of the idea of stabilizing by magnetic wells, Furth and Rosenbluth [25] showed that the linked series of mirror cells of a multiple mirror system could be rendered MHD-stable by proper design of the transition regions between the cells.

Recently, experiments in the Gas-Dynamic Trap mirror experiment [26] at the Budker Institute of Nuclear Physics in Novosibirsk, Russia have shown an additional stabilizing effect, related to the line-tying effect mentioned earlier. In these experiments, in agreement with theoretical predictions, it was shown that if the plasma coming through the mirrors in an axially symmetric mirror cell is exposed to a sufficiently long region of "good-curvature" field lines, the denser plasma inside the mirrors will be rendered MHD stable, even though contained in a configuration predicted to be MHD unstable by the Rosenbluth-Longmire criterion or its equivalent. A detailed discussion of this and other means for the stabilization of MHD modes in axially symmetric open-ended systems is given in a paper by Ryutov [27].

In summary to this point, there now exists a thorough theoretical understanding of MHD instabilities and their stabilization in open-ended systems, backed up by an extensive experimental data base. If required, situations can be created in open systems that suppress MHD-type modes of all orders. This is a situation that cannot be attained in closed systems such as the tokamak, where even under the best of circumstances there remain residual driving effects for higher-order MHD modes, in some cases resulting in plasma turbulence that unfavorably influences particle transport.

B) High-Frequency Instabilities of Velocity-Space Origin

Though capable of being rendered robustly stable against MHD modes, open systems may under some circumstances be susceptible to non-MHD modes of the wave-particle type. The source of these instabilities resides in the non-maxwellian nature of the plasmas that may be confined in open-ended systems. If certain critical conditions are satisfied by the plasma parameters then waves of electrostatic or electromagnetic nature may grow within the plasma, drawing energy from the "free energy" associated with the departures in velocity space of the ion (or electron) distribution functions from a maxwellian distribution. The critical conditions include the length of the plasma and the degree of departure of the distribution functions from an isotropic maxwellian. Early treatments of this type of instability in open-ended systems were given by Harris [28], Rosenbluth [29], Post and Rosenbluth [30], and by numerous other authors. As a result of these theoretical analyses not only were velocity-space instabilities well understood, but the required conditions for their suppression were clearly defined. A summary of the work on velocity-space instabilities and a more detailed bibliography is contained in a review article by the author [31].

In the earliest days of research into open-ended systems wave-particle instabilities presented a major problem, limiting the achievable plasma density in many experiments to values of order 10^{16} m^{-3}, four orders of magnitude below those of fusion interest. With time and increased understanding stabilizing means, for example, so-called "warm-plasma stabilization" [32], control of gradient lengths, and exploitation of Landau-damping effects, were introduced. These various means effectively controlled velocity-space instabilities, allowing the achievement of quiescent plasmas at fusion-relevant temperatures and densities.

As an early example of the appearance of velocity-space instabilities and their stabilization by Landau-damping effects Figure 2 shows the results of an experimental determination of the stabilizing effects of Landau damping on a particular high-frequency instability encountered in the Baseball I mirror experiment at Livermore [33]. The plot shows the boundary between stability (below the line) and instability (above the line). The ordinate of the plot is proportional to plasma density. The parameter plotted on the abscissa, from the theory, is proportional to the product of the plasma potential (determines the peak energy of the electrons producing the Landau damping) and the square of the wave number of the unstable mode. The agreement between theory and experiment is seen to be close, confirming the analysis.

Later, and in a similar way, the effectiveness of warm plasma stabilization of velocity-space modes was shown in the 2XIIB experiment at Livermore. In this experiment neutral beams were employed to build a trapped plasma in a deep quadrupole magnetic well. The results are shown in Figure 3. In the absence of the warm plasma component the buildup is seen to be interrupted by the growth of instabilities. With the warm plasma stream the plasma now builds up in close agreement with the theoretically predicted buildup curve, reaching high density with no evidence of instabilities of either MHD or velocity-space origin.

Following the invention of the tandem mirror idea the concern for velocity-space instabilities in the confined plasma diminished. In a tandem mirror the central plasma, being electrostatically trapped between the end mirror cells, can more nearly approach an isotropic maxwellian state, one that is stable against such instabilities. In this situation another check on the agreement between experiment and "classical" mirror confinement theory can be made. Pastukhov [34] had predicted the parametric variation of plasma loss, over the potential barriers of the tandem mirror, with plasma potential. Figure 4 shows a comparison between Pastukhov's theory and experiment as found in the Gamma 10 experiment at Tsukuba. Again, the agreement between experiment and theory is seen to be close.

In summary to this point, not only have open systems been found to be tractable for theoretical analysis, but this analysis has been largely confirmed experimentally. In important cases it has been found possible to create confined plasmas that approach quiescence, in that confinement times come close to "classical" values, with fluctuation levels believed to be little above thermal values. There is good reason to believe that this situation, that is, confinement close to that determined by purely classical (i.e., collision-related) processes can be achieved at fusion-relevant conditions. However, owing to the reduction of effort on open-ended systems no experimental facilities of sufficient size to explore this possibility exist at the present time. The largest operating mirror facilities are the previously mentioned Gamma 10 tandem mirror experiment at Tsukuba University in Japan and the Gas Dynamic Trap and Ambal experiments at the Budker Nuclear Physics Institute in Novosibirsk, Russia. All three of these experiments, although capable of producing very significant data, are much smaller than the large tokamaks in the US, Europe, and Japan, too small to contain plasmas at the temperatures and densities that would be required in fusion power systems.

V) Charting a New Course for Fusion Research: Some Ground Rules

If we believe that there is now an opportunity to take a new look at the fusion problem with a broader view than that provided by considering only closed magnetic confinement systems, we then need to establish some new ground rules. The first one concerns our mental picture of a fusion system: Closed systems, such as the tokamak or the stellarator, bring with them the picture of a complex coil system of roughly spherical outward shape. Buried inside this structure is a fusion reaction chamber penetrated by beam lines and rf antennas. Access is limited, wall power densities are high, and there is little flexibility for innovative changes of any kind, for example, for the introduction of direct converters.

Contrast this mental picture with that for open-ended systems. Here one can contemplate a whole spectrum of possibilities. At one end of this continuum is a single mirror cell with quadrupolar mirror fields produced by a "baseball" coil, at each end of which would be placed direct converters. Such a system was studied conceptually many years ago by Moir et. al. [35]. The next possibility, also studied in the past in the MARS reactor study [36], is a tandem-mirror system, having plugging cells and direct converters at each end, with modular coils and a long cylindrical confinement chamber located between them. At the far extreme of possible systems would be a long linear system, perhaps many kilometers long, composed of modular sections, and located in a tunnel deep underground. Such a system would resemble the SLAC linear accelerator at Stanford or the "linear colliders" being proposed for high-energy physics research. In what follows I will give as an example a long linear system employing mirror fusion concepts.

In addition to broadening our visualizations of what a fusion power plant might look like our ground rules should include broadening our view of the plasma regimes where such systems might operate. By "regimes" is implied such items as the degree of randomization of the ions of the plasma, and the types of ions present in the system. In closed systems such as the tokamak, particularly those aimed at ignition, collisional randomization insures that the ions and electrons exist close to a maxwellian state. However, in open systems, as noted earlier, the ions may exist far from a maxwellian state, to the point that they approximate directed beams. In such cases the physics issues involved come closer to those encountered in particle accelerators than those pertaining to a gas of maxwellian particles. As far as the fusing ions are concerned, however, since fusion is a binary reaction the particles in undergoing fusion are indifferent as to whether their energy distribution is a maxwellian or whether they are members of colliding monoenergetic beams: Their reaction probability will simply be given by the product of their reaction cross-section and their relative velocity. If it turns out to be advantageous, and in those cases where there are not substantive disadvantages, our ground rules for looking for new approaches should therefore consider the whole spectrum of plasma regimes.

Finally, as has already been discussed, in setting our new ground rules we should abandon the goal of plasma ignition as a requirement, substituting for it the simple requirement of net positive fusion power. In addition, we should be open to consider pulsed systems whose time-averaged energy release is positive. This latter proposition opens the door to "batch processing" types of fusion power generators. It also implies the possibility of taking advantage of time-dependent effects, such as time-of-flight of the particles, or in the extreme limit, inertial confinement effects, however, here in the context of magnetic confinement systems.

The point of laying out some ground rules for a new look at magnetic fusion systems is to attempt to break old habits of thinking. The relationship of this attempt to the subject of this paper is that I am endeavoring to point out the advantages of applying these new ground rules to open-ended systems. In this connection it would be presumptuous of me to try to enumerate a comprehensive list of possible variations on the open-ended theme where investigations might be aimed. I will instead give a simple example of a system that breaks with past tradition and that might be worthy of future study. The main criteria that will be applied to the example system is that it should be capable in theory of yielding net power within the assumptions made in analyzing it, that it does not require extreme extrapolations of technology to implement, and that it is not obviously too expensive ever to compete with other energy sources. The linear system that will be described is an evolutionary descendant of ones that I have discussed before [37,38,39]. Its appearance in this paper is for the purpose of giving substance to my plea for "casting a wider net" in looking for new directions for fusion research, in particular in looking at open systems.

VI) Long Linear Open-Ended Systems for Fusion

The high-energy research community has paved the way for the fusion research community to consider the possibility of constructing fusion power systems in underground tunnels many kilometers long. They have shown the way to solve the land-use problem of locating very large and complex particle-handling systems in an economical way. An example is the 27 kilometer-long Large Electron-Proton Collider at CERN in Switzerland. The tunnel containing the magnets and vacuum chamber of this facility runs below farmland and villages in both Switzerland and France with no interference with those land uses.

The example that we will give, also a "collider," is comprised of a long axially symmetric central solenoidal superconducting magnet coil together with its cryogenic housing and a blanket assembly, inside of which is the fusion reaction chamber. The magnetic field strength tapers up smoothly from each end, approaching its maximum value asymptotically, so that the field lines converge inwardly from each end. Such a field configuration, having positive field line curvature throughout its length, should be stable against MHD modes of the interchange type. As such it represents the simplest possible MHD-stable field configuration for an open-ended system. The issue now becomes one of how one deals with end losses in such systems. In our example we will discuss one possible (very simple) solution involving the time-of-flight of two mutually-colliding ion beams, a system that might therefore be called a "linear collider." In this collider ions are injected, nearly parallel to the direction of the field lines, near the ends of the solenoid, where the field is weak. In traveling up the magnetic gradient the injected ions are compressed radially, increasing the particle density up to that required to achieve net power.

Critical to such colliders are ion injectors and direct converters. located at the ends. These provide the means to create the colliding beams and to recover energy from ions that did not fuse. The technical and economic feasibility of such systems depends on whether or not these elements can achieve high efficiencies in their operation. In the case of the direct converters, previous work [9] has shown that conversion efficiencies of ion kinetic energies to electricity of order 90 percent are achievable, the higher the efficiency the narrower the energy distribution. Well-designed ion sources are also capable of achieving comparable efficiencies. The consequence of achieving high efficiencies in the injectors and the direct converters is, in effect, to multiply the Q_{fus} factor of the fusion reactions by an "electrical Q" that can permit the Q associated with the recovered fusion energy, Q_{fus} , to be actually smaller than unity, still allowing the system Q, to be larger than unity, i.e., indicating net power production. Here we have defined the parameter $Q_{fus} = Q_{fr} \cdot \eta_f$, where η_f is the efficiency of conversion of the fusion reaction energy to electricity, and Q_{fr} is the usual Q value, i.e., the ratio of the fusion energy released to the energy input required to maintain the plasma at fusion temperatures.

$$Q = Q_E \cdot Q_{fus} \qquad Q_E = \frac{\eta_i}{1-\eta_i \eta_{dc}} \tag{7}$$

If the injection efficiency, η_i , and the direct conversion efficiency, η_{dc} , are both equal to 0.9, then $Q_E = 4.7$. In this way a trade-off between confinement requirements and technological development can be accomplished.

VII) A Linear Collider

In this section we will sketch an example of an open-ended system that illustrates the flexibility of this geometry for application to systems that are very different from conventional approaches. The example does not represent a detailed "proposal," but is instead aimed at showing the potential advantages of making a tradeoff that reduces the importance of achieving good confinement in fusion systems in exchange for solving some well-defined technological problems.

The example we will describe probably represents the simplest open system that one could propose that could conceivably become a viable fusion power plant. A particular version of the idea has been described in previously published reports [37,38,39]. In the earlier versions ion sources at one end of the solenoid inject Type A ions and other ion sources at the opposite end inject Type B ions. These ions collide with each other in passing through the tube, and a small fraction of them would fuse with the release of energy. Those ions that did not react would exit the system and enter the direct converters to accomplish the Q amplification described above. If the Type A ions were deuterons, and the Type B ions tritons, then the optimum injection energies for each would be 36 keV and 24 keV, respectively, giving an energy in the center-of-mass corresponding to the maximum point in the D-T reaction cross-section (at 100 keV), at a minimum total ion energy (64 keV). While the ion energies chosen represent optimum values from a colliding-beam standpoint, the configuration carries with it a certain technological problem: With ion sources and direct converters at both ends the problem arises of how to minimize the interception of the escaping ions on the structures of the ion sources so as to maximize their probability of interception by the direct converters. Molecular ion or neutral beam sources might help this endeavor, but they would carry with them additional technical challenges.

Given the issues just described we will here take a somewhat different tack. We will assume a less-than-optimum situation for colliding beams in return for the elimination of the problems just described, as follows: Assume that both the D and the T ion sources are located at one end, and the direct converters are located only at the far end. Here the T ions are injected, up the

magnetic gradient, at such an initial angle that they end up spiraling down the field at a tightly-wound pitch angle. In this way they form a tritium “target” with which the injected D ions, moving down the field also at small pitch angles, can collide. If the energy of the T ions is substantially smaller than that of the D ions the optimum energy of injection of the D ions will be approximately 100 keV. For example, if we choose the energy of the T ions to be of order 10 keV, their velocity is small enough relative to the velocity of the D ions to be ignored in estimating the average reaction cross-section, which will be close to its peak value of 5.0×10^{-28} m^2 . Choosing W_D = 100 keV and ignoring the azimuthally averaged velocity of the T ions relative to the D ions in the calculation then leads to a mean reaction parameter $\sigma_{DT}\, v_{rel}$ = 1.6×10^{-21} $m^3\ sec^{-1}$. This value is about 4 times higher than the maxwellian-averaged reaction parameter for fusion reactions in a DT plasma at 20 keV kinetic temperature. The fusion power density is correspondingly higher than that for maxwellians, being about 60 megawatts/m^3 for D and T ion densities of 10^{20}
m
Error!.

A) Constraints Imposed by the "Firehose" Instability

In estimating the source parameters needed to achieve the desired densities of T and D ions in the collider it is necessary to consider the limitations that are imposed by the “firehose” MHD instability [40]. The firehose instability is driven by the existence of a parallel pressure component, above a critical value, in a frame in which the net momentum is zero. Thus, if in the configuration we have chosen we were to inject monoenergetic ions of only one species the firehose instability could not occur, as there is zero parallel pressure in the frame in which the net momentum is zero. Also, even if we were inject two different species of ion, if their relative energies were such that they moved down the field at the same velocity, the firehose instability would not be stimulated. However, in the present case we are injecting two types of ions at different energies and at different initial densities. Assuming that these beams co-mingle in flight the possibility of the firehose instability arises. In the calculations below we will make a “worst case” assumption, namely that the two beams co-mingle immediately upon exiting their respective ion sources.

For ions injected nearly parallel to the field lines an approximate condition for stability against the firehose instability can be stated in terms of the total parallel ion pressure component and the local strength of the magnetic field is given by equation 8:

$$\Sigma p_{par} = M_D n_D (v'_D)^2 + M_T n_T (v'_T)^2 < \frac{B^2(0)}{\mu_0} \text{, stable} \tag{8}$$

Here the primed velocities of the deuterons and tritons are their velocities in the frame moving at velocity v_0 , defined through equation 9:

$$(M_D n_D + M_T n_T) v_0 = M_D n_D v_D + M_T n_T v_T \tag{9}$$

The most unstable region for this instability is in the vicinity of the sources, the point where the magnetic field is weakest and the ion kinetic energy is directed almost entirely along the field lines. The criterion given by equation 8 can be rephrased as a condition on the ion-source current density, ion energy, and the magnetic field (at its maximum) required to achieve a given compressed ion density. In the expressions below we express the ion-source current densities for both types of ions in units of 3 amperes/cm^2 , the deuteron energy in units of 100 keV, the triton energy in units of 10 keV, the magnetic field in units of 10 Tesla, and the ion densities in units of 10^{20} m^{-3} . In other words, we set $j_D = j_T = 3.0\alpha$ amps/cm^2 , $W_D = 100\,\lambda$ keV, $W_T = 10\,\lambda$ keV, $B_{max} = 10\Gamma$ Tesla, $n_D = 1.0 \times 10^{20}\ \gamma_D\ m^{-3}$, and $n_T = 1.0 \times 10^{20}\ \gamma_T\ m^{-3}$. We will also assume that both species of ions are injected at a small angle with respect to the field lines such that after moving up the magnetic gradient to the high-field region they are spiraling down the field at a pitch angle θ (rad.). With these assumptions the triton density is determined by the deuteron density through the ratio $\gamma_T / \gamma_D = 3.833$.

Considering now the calculation of the parallel pressures in the moving frame we find from equation 9 the velocity of this reference frame as having the value $v_0 = 0.3680\ v_D$. This and the other parameters may now be inserted into the stability condition, inequality 8, to yield a condition on the deuteron density after magnetic compression:

$$\text{For deuterons:} \qquad 27.\left[\frac{\lambda^{3/2}\,\gamma_D^2 \cos^2(\theta)}{\alpha\,\Gamma^2}\right] < 1.0 \text{, stable,} \tag{10}$$

with the triton density being 3.833 times that of the deuteron density.

The choice of 3.0 amperes/cm^2 for the unit of ion-source current density has its origin in pioneering studies of ion-source current limitations in 1979 by Dembrinski and John [41]. In their paper these authors reported the achievement of light-ion current densities in excess of this value by extraction of the ions from a flowing plasma. Using this technique they overcame the usual Bohm-sheath limitation (of order 1 ampere/cm^2) on the current density of conventional ion sources.

The choice of 10 Tesla for the unit of magnetic field is that this level of field can be routinely obtained with large superconducting magnet coils. If justified on economic grounds, even higher fields than 10 Tesla could be obtained for a linear collider. For superconducting coils a long solenoid represents a much more favorable geometry for obtaining high fields than that of closed systems such as the tokamak.

In addition to the constraints imposed by the firehose instability there is a constraint imposed on the pitch angle after compression by the necessity to avoid the "mirror" MHD instability mode for the tightly spirally ions. An approximate condition for stability against the mirror mode is given by the inequality [40]:

$$\frac{\Sigma p_{perp}}{B^2/2\mu_0 + \Sigma p_{perp}} < \frac{\Sigma p_{par}}{\Sigma p_{perp}} \text{ , stable} \qquad (11)$$

where $\Sigma p_{perp} = [n_D M_D v_D^2 + n_T M_T v_T^2] \sin^2(\theta)$ and $\Sigma p_{par} = [n_D M_D v_D^2 + n_T M_T v_T^2] \cos^2(\theta)$. In the limit of $\cos^2(\theta) << 1$ condition 11 becomes:

$$\cos^2(\theta) > \frac{0.111\, \lambda \gamma_D}{\Gamma^2} \text{ , stable} \qquad (12)$$

Now inserting this constraint (as an equality) into equation 10 results in a revised criterion that, insures stability against both modes for both the deuterons and the tritons. The new criterion is:

$$\text{For deuterons:} \quad 3.01 \left[\frac{\lambda^{5/2} \gamma_D^3}{\alpha\, \Gamma^4}\right] < 1.0 \text{ , stable} \qquad (13)$$

with the triton density, as before, being 3.833 times the deuteron density

B) Fusion-Related Parameters

Using the peak value of the reaction cross-section and taking into account the effect of the pitch angle on the deuteron path length we may estimate the reaction probability of a deuteron per meter of the solenoid, finding:

$$R_{DT} = 5 \times 10^{-8} \left[\frac{\gamma_T}{\cos(\theta)}\right] = 1.9 \times 10^{-7} \left[\frac{\gamma_D}{\cos(\theta)}\right] \ m^{-1} \qquad (14)$$

Inserting the constraint on cos(θ) implied by inequality 12 results in an equation reflecting the limits on the reactivity imposed by the mirror instability;

$$R_{DT} = 5.8 \times 10^{-7} \left[\frac{\gamma_D^{1/2}\,\Gamma}{\lambda^{1/2}}\right] \qquad m^{-1} \qquad (15)$$

Similarly, the fusion power density, using the value assumed above for the fusion reaction parameter, is given by the equation:

$$p_{DT} = 57.\,[\gamma_D\,\gamma_T\,] = 218.\,[\gamma_D\,]^2 \quad \text{megawatts/m}^3$$

(16)

We may use equation 14 to estimate a "breakeven length" of our linear collider, i.e., the minimum length of high field solenoid required to yield an amount of electrical power, (converted from the fusion energy released to electricity at an efficiency η_f), equal to the electrical power required to inject the deuteron ion beam (i.e., including ion source and direct converter efficiencies). For this rough estimate we will ignore the lesser power required to inject the low-energy T beam. This length is then given by the equation:

$$L_{min} = 2.3 \times 10^4 \left[\frac{\cos(\theta)\lambda}{\gamma_D Q_E\,\eta_f}\right] \quad \text{meters} \qquad (17)$$

Again, inserting the constraint (inequality 11) on cos(θ) gives a new relation reflecting the limitation imposed by the mirror instability:

$$L_{min} = 7.8 \times 10^3 \left[\frac{\lambda^{3/2}}{\gamma_D^{1/2} Q_E\,\eta_f\,\Gamma}\right] \quad \text{meters} \qquad (18)$$

The expression for the breakeven length may also be used to estimate the breakeven "confinement time" (flight time) of the deuterons through the system, as an index of the diminished confinement time requirements of this linear collider, as compared to conventional fusion systems, such as the tokamak. From equation 17 and the velocity of the deuterons we find the result:

$$\tau_{min} = 7.4. \times 10^{-3} \left[\frac{\lambda^{1/2}}{\gamma_D Q_E \eta_f} \right] \text{sec.} \tag{19}$$

C) An Example Case

We may now use equations 13 through 19 to calculate an example linear collider case. In equation 13 we will assume values for all the parameters except the density parameter, γ_D, finding then the limiting deuteron and triton densities stable against the firehose mode and the mirror mode at all points in their trajectories. We take $\lambda = \alpha = \Gamma = 1.0$ in equation 13 finding $\gamma_D = 0.69$ and $\gamma_T = 2.66$. Inserting these ion density values into equation 16 we find $p_{DT} = 105$ megawatts/m^3 , a rather high power density, one having implications as to the smallness of the diameter of the plasma column that will be needed in the linear collider.

For comparison with conventional fusion systems we may use these same parameters in equation 19 to evaluate the breakeven confinement time of the deuterons. Taking the efficiency of conversion of the fusion energy, $\eta_f = 0.33$ (i.e., assuming a conventional thermal cycle is used), taking the source and direct converter efficiencies, $\eta_i = \eta_{dc} = 0.9$, so that $Q_E = 4.7$, we find $\tau_{min} = 7.$ ms. To be sure the confinement times required for practical net power would be substantially longer than this value, but still would be small compared to those required in a conventional tokamak-based fusion power system.

Equation 18 may be used to estimate the breakeven length of the linear collider. With the parameters assumed above we find $L_{min} = 6.0$ kilometers. As a first cut for the length of our linear collider we might assume L = 15. kilometers, i.e., 2.5 times the breakeven length. Associated with this length would be a deuteron confinement (flight) time of 17.5 ms, and a triton flight time (estimated from the ratio of the deuteron velocity to the triton velocity) of about 45 ms.

If one assumes, for example, that the net power output of the plant is to be 1000 MWe the minimum plasma radius may then be estimated approximately by using the power density as calculated from equation 17 and the fusion energy conversion efficiency that was assumed above. The minimum radius of the column (assumed to be at constant density as a function of radius out to its boundary), is then found to be $a(min) =$ 2.4 cm. This almost ridiculously small radius is a consequence of the projected high fusion power density of our linear collider, coupled with the necessity to have a long plasma column in order to achieve net power. Even if one assumes that the density distribution of the plasma column is parabolic with radius the column diameter would only be of order 10 cm. This diameter is to be contrasted with the plasma diameter of several meters projected for fusion power plants based on the tokamak.

While the example that we have given is for a D-T fusion system, the linear collider idea or its variants could in principle be applied to other fusion fuel cycles, such as D-He3. An economic penalty would be paid because of the smaller fusion cross-section and the higher ion energies required, but other advantages, such as the near-absence of satellite neutron-producing reactions and the elimination of the need for a breeding blanket, could ameliorate this penalty. In fact a case could be made that it should be much easier to scale up an open-ended system, such as a linear collider, to operate with alternate fusion cycles than it would be to contemplate scaling up tokomak-based systems for such cycles.

D) Electron Physics and Other Plasma-Related Issues

In the simple calculations that have been presented some potentially important plasma-related and other issues have not been discussed. It is beyond the intent of this article to deal with such issues definitively, so that the discussion here will be limited to brief comments. One issue, perennially brought up in the discussion of open-ended systems, is the question of end thermal losses associated with the electrons of the plasma. To reduce the effects of electron drag on the ions to acceptable levels the electron temperature of the plasma has to be of order a few keV. To illustrate the point, in the example case the characteristic slowing-down time of the deuterons by electron drag becomes equal to their flight time of 17.5 ms. at an electron temperature of 3.0 keV, representing a probable lower bound to the operating electron temperature.

The issue is the following one: If anything like the normal heat conductivity of the electrons were to prevail at kilovolt electron temperatures the resultant energy loss through the ends would be enormous. Fortunately, as was predicted theoretically [42], and recently confirmed experimentally in the Gas Dynamic Trap experiment [43] at Novosibirsk, the situation is much better than this. In an open-ended system with a central dense plasma that expands into a weakening magnetic field the rate of loss of electrons is controlled by the ambipolar potential that arises naturally in preserving quasi-neutrality. This potential, if it is allowed to rise to its asymptotic value, holds in the electrons, effectively inhibiting their loss rate. Furthermore as the theory predicted and experiment confirmed, if the expansion ratio of the field, that is the ratio of the field at its maximum to that where it terminates on a physical surface is larger than the square-root of the ion-to-electron mass ratio, the electron population becomes decoupled from any interaction with the wall, becoming insensitive to, for example, the emission of secondary electrons at the wall. In this case the energy losses per electron associated with the electron channel are limited to some multiple (of order 5) of the electron mean energy in the plasma. The number of electrons being lost is in turn limited to that associated with any source terms that are present in the plasma.

In the linear collider case here the expansion ratio of the magnetic field at the ends will be substantially larger than Ryutov's critical value. Also, since only completely ionized ions are being injected by the ion sources, the primary source of the electrons in the plasma column is the ionization of the background gas in the system. This source could in principle be made quite small in steady state. We conclude that it may be possible to create a situation where the energy loss through the electron channel out the ends is acceptably small.

Another area where electron-physics issues might impact the operation of a linear collider is the presence of turbulent transport. Although we have addressed all of the “killer” MHD modes (interchange, firehose, and mirror modes) there might still be present small-scale turbulence that could cause excessive cross-field transport. The usual way to estimate this transport is compare it with the Bohm diffusion rate, which represents an approximate upper bound to the rate of diffusion caused by such turbulence. For our example case, assuming a parabolic density distribution with an outer radius of 5 cm., the calculated Bohm diffusion velocity at 3.0 keV is approximately 18 cm./ms. It follows that for the linear collider example that we have given the rate of cross-field transport by turbulence would have to be a substantial fraction of the Bohm rate before it seriously interfered with the operation of the system.

Another effect of the ambipolar potential of the electrons on the collider would be to require that in order to have the ion energies within the collider equal to those assumed above, namely 10 keV for the tritons and 100 keV for the deuterons, the actual ion-source accelerating voltages would have to be increased by an amount equal to the ambipolar potential. At an electron temperature of 3 keV this potential would be of order 15 keV. Of course the injected ions, though losing energy through climbing up the ambipolar potential, would be accelerated by the same potential as they exited. Thus the direct converters would still be operating on D and T ions having energies comparable to the accelerating energy input at the sources. In the interest of simplicity the corrections to the equations for ion source densities, etc., required to take into account the effect of the ambipolar potential, have not been introduced.

E) Some Economic Considerations

If the above physics and engineering considerations are found to be valid, then the calculations presented for the linear collider example would be a reasonable representation of its size and other characteristics. However, whether such a system, even if it proved technically feasible, would ever be built depends on its economic viability. While it is not within the scope of this article to attempt to present a detailed cost analysis of the linear collider that has been described, it is possible to make some simple cost estimates that are informative.

We have already noted that locating a fusion linear collider in an underground tunnel is a feasible means of solve the siting and land-use problem, the way having been paved by the high-energy physics community. Moreover, the cost of tunneling itself is minuscule compared to the cost of the structures within the tunnel and can be neglected. As to the cost of the linear collider itself, a starting point can be obtained by reference to studies that have been made of the cost of large-scale SMES (Superconducting Magnetic Energy Storage) systems for utility use. One particular study [44] involved long solenoidal magnets of the same general character as the ones proposed for our linear collider fusion power system. The results of their study may be used to obtain a rough estimate of the costs of the solenoid for the linear collider. If we assume that the solenoid is 2 meters in inner diameter, is 15 kilometers in length, and operates at 10 Tesla it will be storing about 2.0×10^{12} Joules of magnetic energy. From the reference the cost per megajoule of an entire large SMES system is shown as about \$250. If we make the upper-limit assumption that 100 percent if the cost resides in the solenoid our 15 kilometer solenoid would, under this assumption, be estimated to cost $\$5.0 \times 10^8$ (\$33,000/meter) . If we multiply this figure by 3.0 to account for the other components (blanket, vacuum chamber, etc.) and assume an equal cost for the "balance of plant" we arrive at a capital cost estimate of $\$3.0 \times 10^9$ for the entire 1000 megawatt fusion system, or \$3000/kilowatt. This figure is not inconsistent with the present-day capital cost of nuclear power plants.

F) General Comments

The foregoing discussion of a simple linear collider outlines an extreme case of open-ended systems that might be of value for fusion power purposes. As noted earlier, our linear-collider example is at one end of a continuum of systems at the other end of which is are systems such as the tandem mirror or the "field-reversed mirror" (a field-reversed configuration contained in a mirror cell). In another paper [39] I have discussed a concept, the "kinetic tandem," that represents the melding of the tandem mirror idea with the linear collider. The kinetic tandem utilizes the same mirror compression effect described in this paper to create ion-density peaks at each end of a long reaction chamber. These peaks, in the same manner as was employed in the original tandem mirror idea, generate potential maxima that confine a target plasma through which other injected ions pass to produce fusion reactions. However, as its name implies, the kinetic tandem employs only particle kinetic effects to produce its density peaks, thus requires no end mirror cells to accomplish its purposes. Its field is the same tapered solenoidal field that is utilized in the linear collider. As with this paper, however, the main point in discussing these variants on open-ended systems is to drive home the point of the flexibility of such systems for innovative improvements.

VIII) Summary and Conclusions

In magnetic fusion research we find ourselves in a new situation, one fraught with both problems and opportunities. Fifty years of research has resulted in enormous progress in the understanding of the plasma-physics problems of fusion and in movement toward achieving the plasma conditions required for fusion. And yet we are faced with the situation that the scientific front-runner in fusion - the tokamak - may not be a viable approach to economic fusion power. Our opportunity is therefore to utilize our scientific knowledge base in an informed search for better ways to solve the fusion problem. In this paper some of the characteristics and the physics history of open-ended systems has been presented. The argument has been made that open-ended systems are much more amenable to innovative approaches than are closed ones. To support this thesis an extreme example - the linear collider - has been sketched out. Only time will tell whether it, or other variations on this theme, will prove to be economically viable systems. Our real point here is to attempt to reinstill the spirit of innovation and adventure that marked the early days of fusion research. The major difference between then and now is the understanding of the plasma state, gained by 50 years of hard work and reflected in the choice of the title for this paper. A sub-title might have been: "Fusion's Great Opportunity is Now." The underlying truth is that fusion still represents the best option for meeting our civilization's long-term energy needs.

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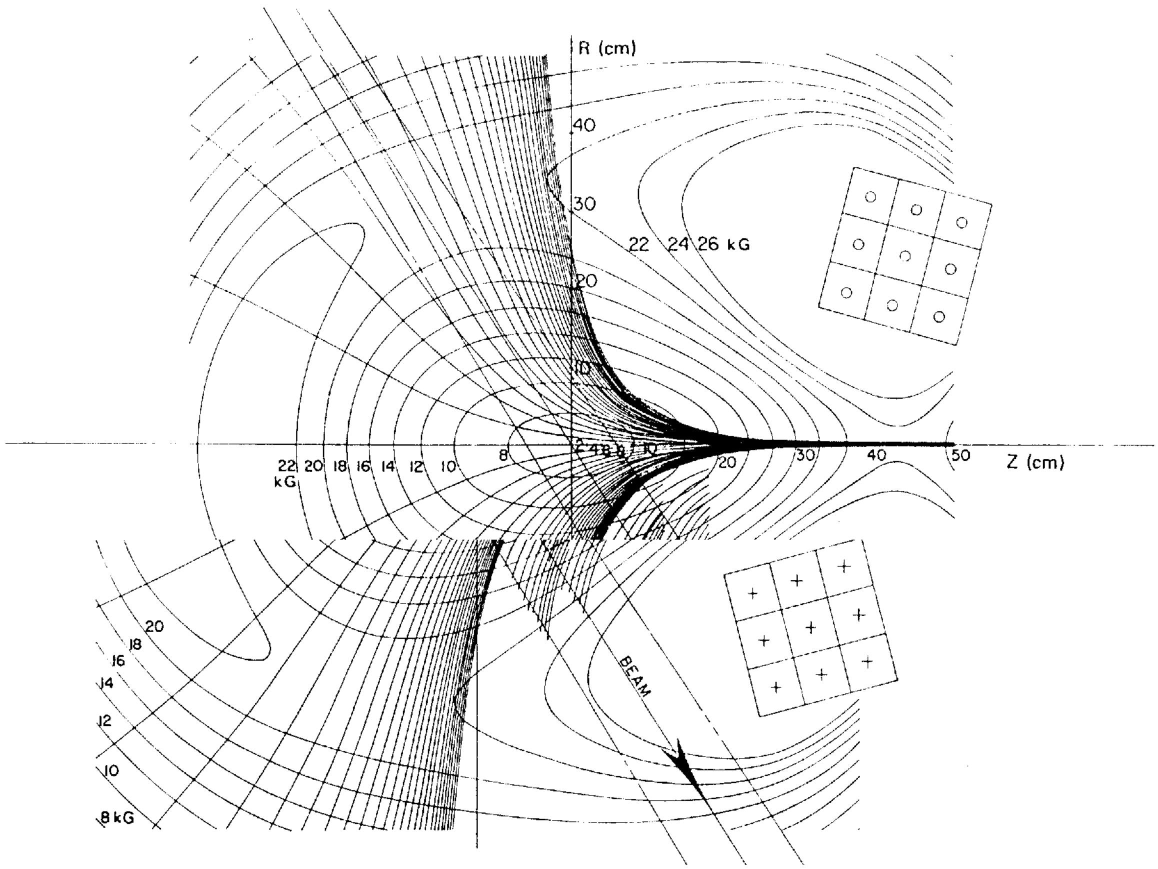

Figure 1

Field lines and field intensity contours calculated for a "baseball" coil

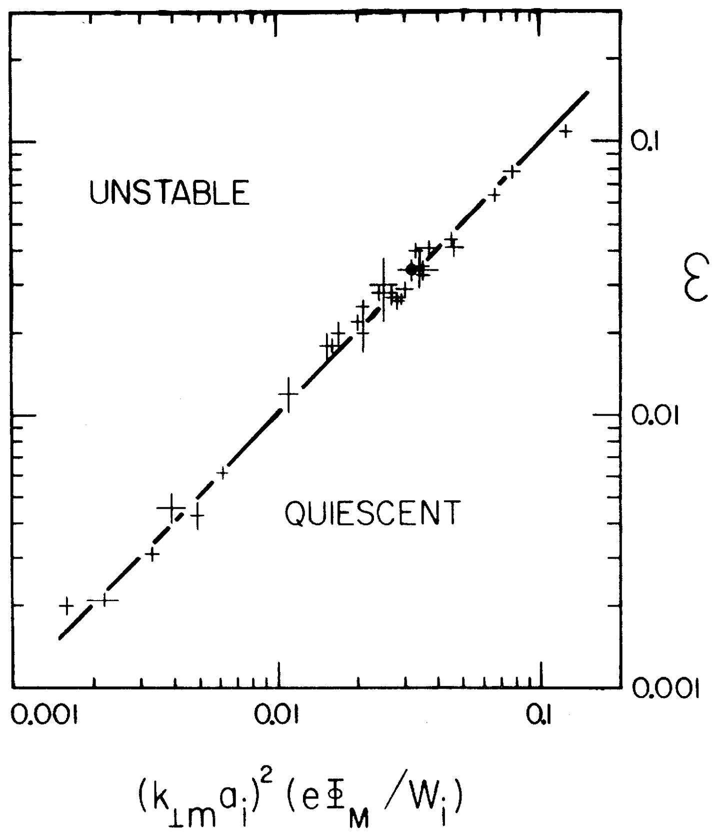

Figure 2

Landau-damping stabilization of ion-cyclotron mode in the Livermore Baseball I experiment: comparison between experiment and theory.

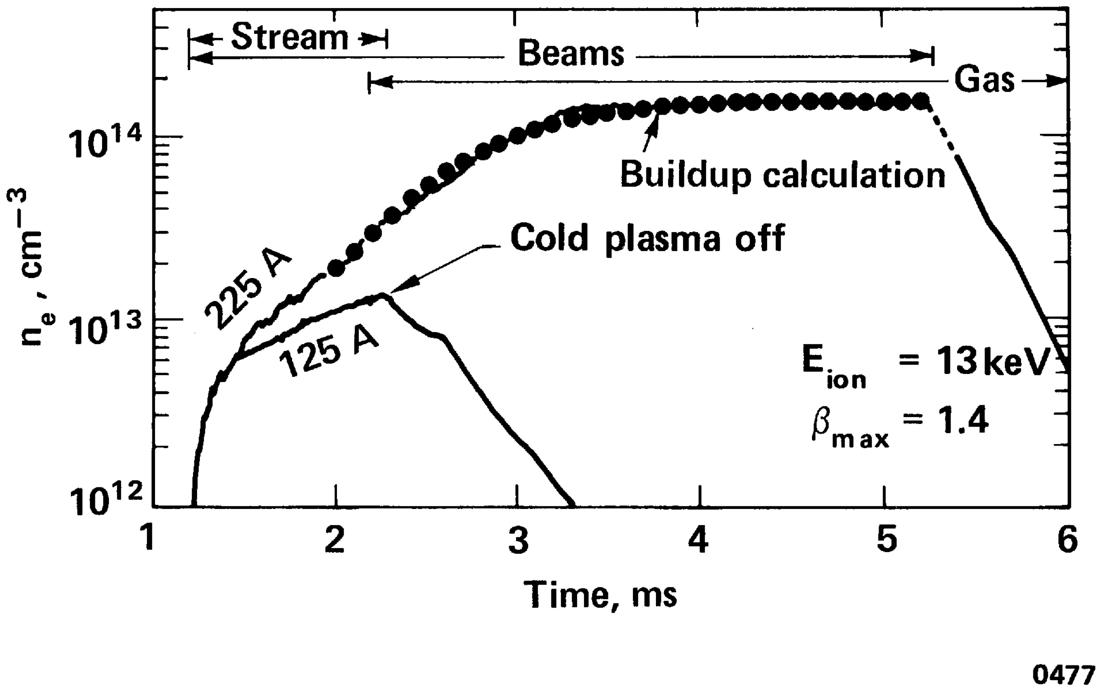

Figure 3

Plasma density buildup vs time in Livermore 2XII experiment showing stabilization of velocity-space instabilities by injecting a plasma stream

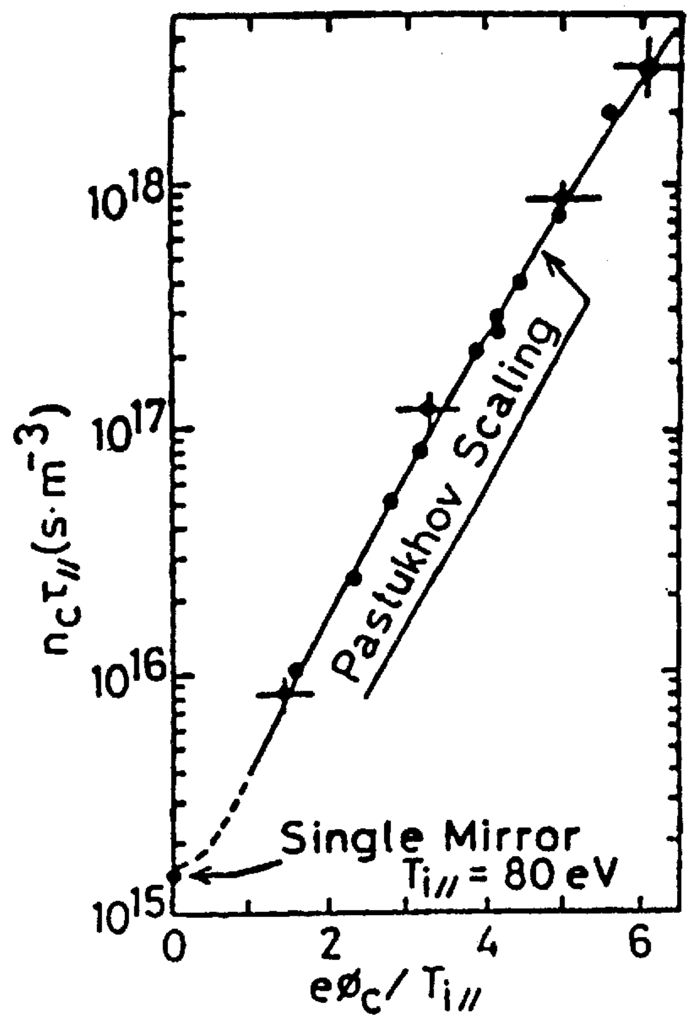

Figure 4

Ion longitudinal confinement time in Gamma 10 experiment: comparison between experiment and Pastukhov theory